DOCKET NO. 11-109

Attachment A

DOCUMENT OFF-LINE

This page has been substituted for one of the following:

o. This filing contains confidential information (Not For Public Inspection)

o An oversize page or document (such as a map) which was too large to be scanned into the ECFS system.

o Microfilm, microform, certain photographs or videotape.

o Other materials which, for one reason or another, could not be scanned into the ECFS system.

The actual document, page(s) or materials may be reviewed by contacting an Information Technician at the FCC Reference Information Center, at 445 12th Street, SW, Washington, DC, Room CY-A257. Please note the applicable docket or rulemaking number, document type and any other relevant information about the document in order to ensure speedy retrieval by the Information Technician.

1 CD-ROM

Original

COVINGTON

BEIJING BRUSSELS LONDON LOS ANGELES
NEW YORK SAN FRANCISCO SEOUL
SHANGHAI SILICON VALLEY WASHINGTON

Gerard J. Waldron

Covington & Burling LLP
One CityCenter
850 Tenth Street, NW
Washington, DC 20001-4956
T +1 202 662 5360
gwaldron@cov.com

EX PARTE OR LATE FILED

May 11, 2016

<u>**BY ECFS and Hand Delivery**</u>

Accepted/Files

MAY 11 2016

Federal Communications Commission
Office of the Secretary

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

DOCKET FILE COPY ORIGINAL

Re: Written *ex parte* presentation in IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091

Dear Ms. Dortch:

On May 9, 2016, Dennis Roberson, Ken Zdunek, and John Grosspietsch with Roberson and Associates ("RAA"); Reed Hundt, counsel to Ligado Networks; and the undersigned met with Ron Repasi, Michael Ha, and Paul Murray of the Office of Engineering and Technology; Charles Mathias of the Wireless Telecommunications Bureau; Jennifer Tatel of the Office of General Counsel; and Karl Kensinger and Robert Nelson of the International Bureau. We discussed the attached materials concerning the results of testing conducted by RAA with respect to whether deployment of LTE in adjacent bands affects the ability of GPS devices to provide consumers with accurate location information. This material is being submitted in response to the Commission's recent Public Notice seeking comment on the company's license modification applications.[1] This material is being filed with the Commission both electronically and in hard copy with the Secretary. Accompanying the hard copy filing is a CD containing RAA data in Excel format.

No. of Copies rec'd 0
List ABCDE

[1] *See Comment Sought on Ligado's Modification Applications*, Public Notice, IB Docket Nos. 11-109 & 12-340, DA 16-442 (April 22, 2016).

Please direct any questions to the undersigned.

Sincerely,

/s/ Gerard J. Waldron
Gerard J. Waldron
Dustin Cho
Counsel to Ligado Networks LLC

cc: Mr. Ron Repasi
Mr. Paul Murray
Mr. Michael Ha
Mr. Charles Mathias
Ms. Jennifer Tatel
Mr. Karl Kensinger
Mr. Robert Nelson

Attachments

ligado NETWORKS

TABLE OF CONTENTS

COVINGTON

BEIJING BRUSSELS LONDON LOS ANGELES
NEW YORK SAN FRANCISCO SEOUL
SHANGHAI SILICON VALLEY WASHINGTON

Gerard J. Waldron

Covington & Burling LLP
One CityCenter
850 Tenth Street, NW
Washington, DC 20001-4956
T +1 202 662 5360
gwaldron@cov.com

May 9, 2016

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

Re: Written *ex parte* presentation in IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091

Dear Ms. Dortch:

This letter is being submitted to provide the results of the test program that Roberson and Associates (RAA) completed to determine whether deployment of LTE in adjacent bands affects the ability of GPS devices to provide consumers with accurate location information. As the attached documents demonstrate, RAA concludes that Ligado's utilization of the spectrum assigned to it for LTE deployment is clearly compatible with existing GPS operations as implemented by leading device manufacturers. The study verifies that the agreements Ligado filed with the Commission in December 2015 do indeed ensure that all consumers using GPS-equipped devices can be confident that their devices will perform as the manufacturers promised if Ligado uses its spectrum for wireless broadband consistent with the power limits agreed to between Ligado and the three main GPS device firms, Garmin, Deere, and Trimble. The study further confirms that, for certain industrial uses, many GPS devices are designed in such a way that they can co-exist with Ligado's proposed network; other devices will not be used near any network facility or can be retrofitted cost effectively well before Ligado's network would begin operation.

The RAA team conducting the study collectively has over 130 years of experience in wireless communications, spectrum management, systems engineering, and related fields. Over the past nine months, RAA designed and conducted an innovative testing program designed to measure what, if any, effect Ligado's proposed terrestrial broadband operations would have on the ability of GPS devices in various market segments to accurately provide position measurements. RAA first tested a device's baseline ability to accurately measure its position in the absence of any LTE signals by comparing the device's reported position with the device's "true" position. RAA then compared the device's baseline performance with the device's performance in the presence of adjacent band LTE signals under the parameters Ligado has proposed in its December 2015 application to modify its licenses.

RAA developed its test plan based on a transparent, iterative process that took into account feedback from a wide variety of stakeholders. RAA shared its initial outline of testing procedures with the Commission and the Department of Transportation ("DOT") in June 2015,[1] filed a draft test plan with the Commission in August 2015,[2] and conducted an open discussion regarding the test plan at DOT's October 2, 2015 workshop on adjacent band issues. At each stage of the process, RAA and Ligado encouraged device manufacturers and other interested parties to provide feedback and any available technical data — on a confidential basis to RAA only, as needed — to make RAA's study as robust as possible. RAA made several refinements to its test procedures in response to feedback from stakeholders, including developing a method to test General Location and Navigation ("GLN") devices in simulated motion in response to a leading consumer GPS manufacturer's suggestion.

RAA's study thus provides policymakers with actionable data on the practical effect of Ligado's proposed terrestrial broadband operations. This study provides critical information necessary for the Commission and other stakeholders to assess whether Ligado's operations at the reduced power levels succeed in not causing harmful interference to GPS devices;[3] this information also enables the Commission to advance the public interest by promoting the development and rapid deployment of new technologies, products, and services for the benefit of the public and the efficient and intensive use of the radio spectrum.[4] RAA's study shows that Ligado's license modification proposal serves both of these goals.

---

[1] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed June 24, 2015).

[2] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed Aug. 25, 2015).

[3] *See* 47 C.F.R. § 2.1(c) (defining harmful interference as "[i]nterference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the International Telecommunication Union] Radio Regulations."); *Comment Sought on Ligado's Modification Applications*, Public Notice, IB Docket Nos. 11-109 & 12-340, DA 16-442, at 8 n.48 (April 22, 2016) (citing 47 C.F.R. § 2.1(c)) ("*Modification PN*").

[4] *See generally* 47 U.S.C. § 309(j)(3)(A), (D) (directing the Commission to pursue these policy goals as it considers spectrum policies such as allocations and assignment by auction).

Specifically, RAA's testing found the following about the classes of GPS devices:

- **Consumer Devices**
    - **General Location and Navigation:** All 12 GLN devices tested — representing five manufacturers — maintained their baseline GPS position accuracy in the presence of Ligado's proposed operations under "Open Sky" conditions. Even when presented with GPS signals 16 times weaker than the levels a GPS receiver would experience outdoors with an unobstructed view of the sky, only one of these 12 devices showed any effect from LTE operations — an effect that appeared in only one of the four proposed LTE bands, only when the device was in motion, and at LTE power levels that will occur with extremely low probability.
    - **Smartphones and Tablets:** RAA completed testing on three cellular devices (one tablet and two smartphones), which all maintained their baseline GPS position accuracy in the presence of Ligado's proposed operations. In fact, comparing the performance of the Samsung Galaxy S6 with its predecessor, the S5, shows that cellular GPS devices' performance, which already is highly robust, continues to improve. This is consistent with the fact that cellular devices include multiple transmitters and receivers (cellular in multiple bands, Bluetooth, Wi-Fi, etc.) collocated with the GPS receiver, which necessitates a design tolerant of other signals.
- **Industrial Devices (High Precision):** RAA completed testing on a total of 11 devices, produced by four manufacturers.[5]
    - Two manufacturers offer devices that, in stock condition, maintain their baseline GPS position accuracy in the presence of Ligado's proposed operations. Four of the 11 tested devices are in this category.
    - One of these manufacturers also offers devices that, although they show an impact from Ligado's proposed operations in stock condition, showed no such impact when the device's stock antenna was replaced with a filtered antenna. Three devices are in this category.

[5] Due to technical issues, RAA was unable to obtain useable data from one additional device, the Deere Starfire 3000. In any case, however, Deere does not object to Ligado's proposed operations, subject to the December 2015 license modifications Ligado has requested from the Commission.

- One manufacturer's device is intended for agriculture use, and accordingly would be unlikely to experience the received LTE power levels in a real world environment at which the device showed a performance impact in the test environment.

- The remaining manufacturer offers devices that show an impact from Ligado's proposed operations only in the 1526-1536 MHz band. Three devices are in this category. However, RAA's analysis did not consider the effect of any additional power limits Ligado may be subject to in connection with its request that the FCC condition Ligado's licenses on power limitation requirements for that band necessary to achieve compatibility with current and future MOPS that are incorporated into an active Technical Standard Order from the FAA. It is reasonable to expect that the operational power limitation restrictions necessary to satisfy the FAA requirements will resolve any issues with these devices operating in the 1526-1536 MHz band.

- **Non-Certified Aviation Device:** This device maintained its baseline GPS position accuracy in the presence of Ligado's proposed operations.

In short, RAA's results show that Ligado's license modification proposal — which was developed through discussions with the three leading GPS manufacturers[6] — is compatible with devices in the largest GPS market segments, and that even in segments with more demanding requirements, leading manufacturers already are able to produce devices that coexist with Ligado's proposed operations.[7]

In addition to the power limits tested by RAA, Ligado also has asked the Commission to modify its licenses to reduce substantially its out-of-band-emission limits. Specifically, the license modification application, cementing the changes agreed to by the company in its agreements with the three largest GPS device companies, would reduce OOBE power spectral density from -95 dBW/MHz to -105 dBW/MHz in the GPS band. That means Ligado's devices would operate at 10 times lower OOBE power spectral density than of the previously authorized OOBE levels in the 1559–1605 MHz band to protect GPS, and 800 times lower OOBE at 1610 MHz. This substantially reduced OOBE limit provides additional protection to GPS devices.

[6] *See* Letter from Gerard J. Waldron, counsel to Ligado Networks, LLC, to Marlene H. Dortch, Secretary, FCC, IB Docket Nos. 12-340 and 11-109, RM-11681, at 1-2 (filed Feb. 24, 2016).

[7] RAA's testing did not include certified aviation devices because, as Ligado explained in its Applications, these devices will operate in deference to power limitation requirements for the 1526-1536 MHz band necessary to achieve compatibility with current and future MOPS that are incorporated into an active Technical Standard Order from the FAA. The company's consultation process with FAA and industry stakeholders is ongoing and Ligado's assessment of aviation devices will be undertaken consistent with FAA, RTCA and industry practice.

Attached is a summary report from RAA reporting its results (Attachment B). Also attached are (1) RAA's narrative description of the testing process and results (Attachment A); (2) a detailed presentation of RAA's results for each device (Attachment C); and (3) RAA's final test plan (Attachment D). In addition, RAA is making the results for each device (shown in graphical form in Attachment C) publicly available in Excel format.

Please direct any questions about the study or its implications from any stakeholders to the undersigned.

Sincerely,

<u>/s/ Gerard J. Waldron</u>
Gerard J. Waldron
Michael Beder
Counsel to Ligado Networks LLC

cc: Mr. Ronald Repasi
Mr. Paul Murray
Mr. Charles Mathias
Ms. Jennifer Tatel
Mr. Robert Nelson
Ms. Jessica Almond

Attachments

Roberson and Associates, LLC
Technology and Management Consultants

Results of GPS and Adjacent Band Co-Existence Study

Prepared for Ligado Networks LLC by:

Roberson and Associates, LLC
Chicago, Illinois

Authors:

Dennis Roberson
Kenneth J. Zdunek, Ph.D.
John Grosspietsch, Ph.D.
Bill Alberth

Roberson and Associates, LLC
Technology and Management Consultants

Date: May 9, 2016

Results of GPS and Adjacent Band Co-Existence Study

As Ligado Networks ("Ligado") has previously shared with the Commission, Ligado's counsel hired Roberson and Associates ("RAA") to conduct tests on whether deployment of an LTE network in channels adjacent to spectrum used for GPS, using the parameters Ligado has applied for in the above-captioned license modification applications, affects the ability of GPS devices to provide consumers with accurate position information. This is the key question in assessing whether Ligado's proposed operations would cause any harmful interference to GPS devices.

Accordingly, we set out to test 29 GPS devices, including general location and navigation ("GLN"), cellular, non-certified aviation, and high-precision devices.[1] Having completed our testing, we conclude that Ligado's proposed LTE deployment is clearly compatible with existing GPS operations as implemented by leading device manufacturers. Specifically, we found that the cellular and general location devices we tested were generally unaffected by Ligado's proposed operations under virtually all conditions. Together, cellular and general location devices account for more than 93 percent of all GPS devices installed as of 2015.[2] Certain other devices — primarily high-precision devices using stock antennae — showed greater effects in the proposed lower downlink and lower uplink bands. All affected devices that were able to be re-tested with a filtered antenna became compatible with Ligado's proposed operations in all bands when using the new antenna.

This report summarizes and explains both the test plan RAA developed — with feedback from a variety of stakeholders — and the results of RAA's testing. The results are set forth in further detail in the summary presentation attached to this report as Attachment A and in the detailed presentation of results attached as Attachment B. RAA's final test plan (the "Test Plan") is attached as Attachment C.

1. Background and Summary

RAA is a technology and management consulting company with extensive experience analyzing a variety of spectrum issues, including analyses involving:

- Compatibility of unlicensed Wi-Fi and licensed wireless broadband service
- Compatibility of unlicensed Wi-Fi and mobile satellite services spectrum

---

[1] We tested a non-certified aviation device in addition to the 28 devices listed in the test plan filed with the Commission in February 2016.

[2] *See* GPS Device Market and Supply Chain Overview, at 3, attached to Letter from Gerard J. Waldron, counsel to Ligado Networks LLC, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.* (filed Feb. 11, 2016) ("GPS Market Overview").

- Sharing of recently auctioned AWS-3 spectrum with government operations
- Coexistence of wireless broadband services with current digital television broadcast standards

Dennis Roberson is RAA's Founder, President and CEO, and also serves as the Vice Provost for Research and as a Research Professor in Computer Science at Illinois Institute of Technology. He came to these positions after having served as Motorola's Executive Vice President and Chief Technology Officer. In 2013, with Tom Wheeler's ascension to the role of FCC Chairman, Mr. Roberson was appointed to serve as Chairman of the FCC's Technological Advisory Council, a body he has served on for 18 years. He also has served as a member of the Commerce Spectrum Management Advisory Committee for the past 4 years, most recently based on an appointment by Commerce Secretary Penny Pritzker. In this role he serves as an advisor to Assistant Secretary of Commerce Larry Strickling and the NTIA leadership on various government spectrum matters.

Other members of the RAA team have similarly deep experience:

- Bill Alberth, a senior consultant for RAA, has over twenty-five years of experience in digital communications, systems engineering, digital signal processing, and new technology introductions. His prior positions include service as Vice President and Chief Technology Officer of Mobile Devices at Motorola Mobility, as an advisor to Northwestern University's Department of Electrical Engineering and Computer Science, as a member of the advisory boards for NextNav, LLC, and SiNode, and as a senior advisor for Argonne National Laboratories.

- Dr. John Grosspietsch, a Principal Engineer at RAA, has over 25 years of experience in wireless communications including transceiver and integrated circuit design for cell phones, software defined radio, spectrum compatibility, and cellular and public safety standards. Prior to joining RAA he was a Fellow of the Technical Staff at Motorola Solutions and managed the Enterprise Mobility Research group. He chaired the Software Defined Radio Forum Working Group, and has 15 U.S. patents and 25 technical publications.

- Dr. Ken Zdunek, Vice President and CTO for RAA, has over 35 years of experience in wireless and cellular communications, is a Fellow of the IEEE, and an Adjunct Professor at the Illinois Institute of Technology. Prior to joining Roberson and Associates, he was Vice President of Networks Research at Motorola. He holds 17 patents in the wireless communications area, two of which received "Patent of the Year" recognition by Motorola.

Applying this extensive experience, and assisted by testing and technical support professionals, we developed a test plan designed to rigorously assess whether Ligado's proposed terrestrial broadband operations would cause "harmful interference," which the Commission for decades has defined as follows: "Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the International Telecommunication Union] Radio Regulations."[3] Under this standard, "harmful interference" to a GPS device would be interference that endangers or seriously degrades the ability of the GPS device to measure and accurately report the data the device is designed to provide to users: principally, the device's position.

We designed and conducted a testing program that has successfully measured whether Ligado's proposed operations would diminish the ability of General Location and Navigation (GLN), cellular, non-certified aviation, and high-precision GPS devices produced by leading manufacturers to report their position. As set forth more fully below and in the final Test Plan provided as Attachment C, we first tested each device's baseline ability to accurately measure its position by comparing the device's reported position with the device's "true" position. (The true position was either the position programmed into an industry standard GPS signal simulator emulating GPS signals or, for devices tested using the Live Sky method described below, the position estimated from a long term average of the position reported when no LTE signals were present.) We then compared the device's baseline performance with the device's reported position in the presence of adjacent band LTE signals under the parameters Ligado has proposed. We determined whether a device experienced harmful interference by comparing the average position error (measured over 3 minutes) in the positions reported by the device under baseline conditions (*i.e.*, without the Ligado LTE signals) to the 3-minute average error in the positions reported by the device in the presence of the LTE signals.

Our approach thus is designed to provide the Commission and NTIA — the agencies entrusted with the management of private and federal spectrum, respectively — with actionable data on the practical effect of Ligado's proposed terrestrial broadband operations. Our testing protocol accordingly is superior to proposals that attempt to assess interference based on a proxy measurement such as carrier-to-noise spectral density ratio (C/N_0). For instance, the Department of Transportation's Volpe Center has, for the past several years, been attempting to design and conduct an Adjacent Band Compatibility Study ("ABS") to measure the potential effect of terrestrial broadband operations in spectrum bands adjacent to GPS. The ABS Test Plan released this past March — like earlier drafts of the plan — proposes to develop "interference tolerance masks" based on the "received interference test signal power level that causes a 1-dB [carrier-to-

---

[3] *See* 47 C.F.R. § 2.1(c); *Comment Sought on Ligado's Modification Applications*, Public Notice, IB Docket Nos. 11-109 & 12-340, DA 16-442, at 8 n.48 (April 22, 2016) (citing 47 C.F.R. § 2.1(c)).

noise density] degradation."[4] However, there is no evidence that a change of 1 dB in the carrier-to-noise density ratio correlates to any significant error in a GPS device's reporting of position or timing data, and thus no evidence that such a change in C/N_0 is in any way indicative of the presence of harmful interference. In fact, the results of our testing show the opposite: we found no meaningful correlation between such a 1 dB change and GPS performance.

2. Testing the Effect of Proposed Ligado Operations on GPS Performance

2.1. Test Plan Development

We developed our plan for testing GPS key performance indicators based on a transparent, iterative process that took into account feedback from a wide variety of stakeholders.

We shared our initial outline of testing procedures with the Commission, the Department of Transportation ("DOT") and other organizations in June 2015,[5] filed a draft test plan with the Commission in August 2015,[6] conducted an open discussion regarding the test plan at DOT's October 2, 2015, workshop on adjacent band issues, and filed a revised test plan with the Commission in February 2016.[7] At each stage of the process, we and Ligado encouraged device manufacturers and other interested parties to provide feedback and any available technical data — on a confidential basis to RAA only, as needed — to make our study as robust as possible. The National Public Safety Telecommunications Council (NPSTC) provided feedback on test parameters important to public safety GPS applications, including the range of LTE power levels that should be tested, and a GPS device manufacturer communicated the importance of testing GLN devices in motion.

Our initial plan, like our final plan, focused on measuring what, if any, effect Ligado's proposed terrestrial broadband operations would have on the ability of GPS devices in various market segments to accurately provide position measurements. However, we refined our test

---

[4] Test Plan to Develop Interference Tolerance Masks for GNSS Receivers in the L1 Radiofrequency Band (1559-1610 MHz), at 3, *available at* http://ntl.bts.gov/lib/57000/57000/57046/DOT_GPS_Adjacent_Band_Test_Plan_Final_03012016.pdf.

[5] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed June 24, 2015).

[6] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed Aug. 25, 2015).

[7] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed Feb. 24, 2016).

plan in several ways in response to the comments we received at the DOT workshops and through other channels. For instance:

- In response to concerns that GPS devices in motion may be more vulnerable to performance degradation than devices at rest, we added the ability to test GLN devices in simulated motion.

- We tested with LTE power levels up to -10 dBm (measured at the GPS device), even though this level is not expected to be observed with any significant probability in a commercially deployed system with Ligado's proposed terrestrial broadband operating parameters.

- We tested with uplink signals occupying the full 10 MHz LTE bandwidth based on stakeholder feedback.

2.2. Summary of Final Test Methodology

Device Selection: GPS is used in a wide variety of applications. GPS industry data set forth in the GPS Market Overview[8] identifies the various categories of the GPS receiver market. Cellular handsets represent the largest of these categories based on the number of devices installed in the market, followed by GLN devices. At the same time, although high precision devices represent a much smaller segment of the GPS market, these devices are among the most likely to be vulnerable to interference because many of these devices have relatively wide RF front end bandwidths in order to receive an MSS (Mobile Satellite Service) augmentation signal in the adjacent 1525-1559 MHz MSS band. Taking these factors into account, we selected for testing GLN, cellular, and high precision devices, as well as a non-certified aviation device, that are produced by leading manufacturers and for which it was feasible for third parties to access Key Performance Indicators reported by the device. We also took into account the fact that manufacturers in the GPS consumer device industry share a largely common supply chain and use similar or identical GPS consumer device component parts.

Key Performance Indicators and Other Statistics: The purpose of our study was to collect supporting data to establish the impact on Key Performance Indicators (KPIs) that a GPS device user or application may experience in the presence of L-band LTE downlink and uplink signals within the parameters Ligado has proposed for terrestrial operations. The fundamental KPI for GPS devices used for navigation is position error, *i.e.*, how closely the position reported by the device matches the device's true position. Because of variations in the use cases for different classes of GPS devices, the precise KPI definition varies among these classes.

---

[8] *Supra* n.2.

- GLN: The KPI for this class of device is two-dimensional position error while the device was in simulated motion.

- Cellular: Industry-standard KPIs for GPS performance in cellular devices are set by the 3GPP.[9] We performed three tests defined in 3GPP Specification TS 37.571-1, which measure device sensitivity, accuracy, and dynamic range. Success in these tests is defined by the Specification as the device limiting two-dimensional position error and maximum response time below certain thresholds under defined conditions at least 95% of the time. The 3GPP tests require the device to make phone calls and respond to requests to report position. Since the Samsung Tablet (a cellular device) could not make phone calls and perform the 3GPP tests this device was tested for two-dimensional position error in the presence of LTE signals.

- High Precision: The KPI for this class of device is three-dimensional position error.

- Non-Certified Aviation: The KPI for this device is two-dimensional position error.

In addition to the KPIs set forth above, we recorded other information, such as C/N_0 values and the number of satellites received, to the extent the tested devices reported such statistics in a format accessible to third parties.

Test Setup: Each tested device was placed in an RF anechoic chamber housed at AT4 Technologies, a testing facility in Herndon, Virginia.[10] A Spirent GPS signal generator was used to produce controlled GPS signals for these tests (except for tests conducted using the Live Sky method described below). For exact test setup conditions, see the RAA test plan attached as Attachment C.

GPS Signal Conditions: Several different radiated GPS signal conditions were used, as appropriate for the typical use cases of the different classes of GPS devices. We conducted both "Live Sky" and "Simulated Signal" testing. Live Sky testing used real GPS satellite signals, and we accordingly had no control over the GPS signal power levels. Simulated Signal testing used GPS satellite signals generated by a Spirent GNSS signal generator. For these tests, we had complete control over the GPS signal power levels.

---

[9] The 3GPP (3G Partnership Project) is the internationally recognized standards organization for cellular. *See* http://www.3gpp.org/about-3gpp

[10] *See* https://www.at4wireless.com/index.html

Two forms of Simulated Signal testing were conducted for GLN devices: "Open Sky" and "Impaired GPS Signal." For the Open Sky tests, the Spirent signal generator was configured to provide a nominal received GPS signal level of -130 dBm for all GPS satellites in view. The GPS L1 C/A-code signal-in-space specification is a minimum -128.5 dBm signal level at the output of a 3 dBi linearly polarized antenna. The nominal maximum is -123 dBm, so the simulated clear sky signals were nominally received 1.5 dB to 7 dB below what the receiver under test would have seen outside with an unobstructed view of the sky.

For the Impaired GPS Signal tests, the Spirent signal generator was configured to provide a nominal received GPS signal level of -142 dBm for all GPS satellites in view. This is 12 dB (a factor of 16) below the simulated Open Sky signal level. Referring to the signal-in-space specification above, -142 dBm is 13.5 to 19 dB below the GPS signal levels a GPS receiver would experience outdoors with an unobstructed view of the sky.

The different GPS signal conditions used in the testing were as follows:

- Open Sky: The Spirent simulator created a moving constellation of GPS signals representative of a static location, which were presented to the devices under test along with LTE signals. This method was predominantly used for high precision devices.

- Open Sky with Motion: The Spirent simulator created a moving constellation of GPS signals representative of a moving vehicle, which were presented to devices along with LTE signals. To simulate motion, a "golden" file of position (latitude-longitude) versus time was recorded in NMEA format while driving in a test loop. This file was then loaded into the GPS simulator, along with the date and time of the simulation's start. The simulator then calculated the relevant GPS satellite orbits and generated ideal GPS satellite signals to the device under test as if the device were moving over the test route at the simulated speed. This method was used for GLN devices and the Samsung tablet.

- Impaired GPS Signal with Motion: The Spirent simulator created a moving constellation of GPS signals representative of a moving vehicle (using the same motion-simulation procedure described above). The GPS signals' power levels were reduced as described above to simulate an impaired condition and presented to the devices along with LTE signals. This method was used for GLN devices.

- Live Sky: A rooftop antenna captured outdoor GPS signals which were conveyed into the test chamber and presented to devices along with LTE signals. Live Sky testing was used for high precision devices with MSS augmentation. This approach was utilized because the signal received by the active outdoor antenna included the augmentation signal. This made it convenient to test the device in the condition it was designed for, namely higher accuracy or precision enabled by the satellite based augmentation signal.

LTE Signal Conditions: LTE uplink and downlink signals were generated in the bands Ligado has proposed for such terrestrial broadband use, using the out-of-band emission limits proposed by Ligado, and utilizing a range of power levels including levels that exceeded the limits proposed by Ligado, such that the correct LTE signal and noise levels were present at the GPS receiver under test. The full 10 MHz bandwidth version of LTE signals was used in the measurements.

- Downlink LTE signals were assumed to be supporting many devices and have all LTE resource blocks assigned.
- Uplink LTE signals were representative of a high data rate, with the extreme condition of all resources blocks assigned. The high data rate case is the extreme worst case since this represents an entire sector of a base station dedicated to one single mobile device. Lower data rates will be experienced in the field as well as lower radiated power, since a base station will rarely if ever assign 100% of the resources to a single device located at the edge of a cell. A wideband white noise generator output combined with the LTE uplink signal was used to produce a test signal with the power spectral density matching Ligado's proposed limits for uplink OOBE projected from a Ligado device to a GPS receiver.

When considering the receive signal levels from the Ligado Network's LTE user equipment (UE), the following analysis was considered in determining the power present at a GPS receiver at a one-meter separation distance. To arrive at the received signal under Ligado's proposed power level at the GPS receiver antenna of -19 dBm, the following calculations were used, which are consistent with the TWG report Section 3.2.10.2[11]:

Parameter	Value	Unit	Description
Device UE TX Power	23	dBm	Maximum value per 3GPP standard
Path Loss at 1 meter	37	dB	Free space

[11] Appendix to *Final Report, 2011*, accessed at http://apps.fcc.gov/ecfs/document/view?id=7021690471

GPS Device Gain towards LTE Device	-5	dBi	Combination of TX antenna gain and Rx antenna gain of the cellular devices (assumed by TWG Cellular Subgroup after reviewing empirical data submitted by cellular operators)
Received power after GPS antenna	-19	dBm	Calculated (Device TX Power – Path loss + GPS Device Gain)

[For the downlink power level from the Ligado network's base stations, analysis of the field test data from the 2011 FCC TWG Las Vegas trials was used as a basis for determining the power to a GPS receiver on the ground. The TWG data shows the 99% CDF value for Dense Urban environment to be -35.3 dBm; -20.4 dBm for Urban and -22.5 dBm for Suburban. Specifically, for the case of Rural morphology, the distribution of measurement points in the TWG tests was not uniform over the coverage area of the base station, but clustered closer to the base station tower, improperly biasing the CDF to higher signal strengths. Therefore, in the case of Rural, a Monte Carlo model was used to generate a uniform set of measurement locations over its entire RF coverage area using an underlying free space propagation model. The resultant Rural CDF calculations arrive at a value of -24 dBm for 99% CDF. To set the expected downlink signal value the largest value of -20 dBm (Urban) was selected.]

To ensure the correct LTE signal level at the GPS receiver, the received LTE power was measured with a calibrated antenna of known gain placed in the position of the device under test and oriented toward the LTE emitter.

Test Sequence:

- We first established a baseline for each device's performance under "no interference" conditions in each proposed Ligado band and under each of the applicable GPS signal conditions described below. This was accomplished by recording two hours of measurements for each device with only GPS signals present (*i.e.*, without any adjacent-band LTE signals). The two hour "settle time" was arrived at through an extensive process of evaluating various times and observing that two hours was a sufficient time for the devices to settle into a consistent level of GPS performance.

- The LTE signal (plus a fixed amount of out-of-band "white noise" simulating device Out of Band Emission (OOBE), which was applied when testing proposed uplink bands) was then applied, starting at -80 dBm, with the LTE levels incrementing until reaching -10 dBm.

- We recorded data for three minutes at each LTE level, producing a sufficient number of samples to calculate reliable KPI averages and standard deviations.

- When testing of a device was complete, we reviewed the raw data for any indications that the testing deviated from the test plan (for instance, apparent inconsistencies between the GPS only data and the GPS with LTE data, C/N_0 measurements inconsistent with the test setup, or missing data points). If we observed anomalies suggesting a test had deviated from the test plan in a manner that may have affected the test's validity, the device was retested.

Analysis: The post-measurement analysis of the data involved comparison of the measured received estimated positions with the true values. For GLN and high precision devices, we considered the LTE test condition to have "no impact" on GPS performance if there was no increase observed between the average errors in the relevant KPIs reported by the device under "baseline" conditions and the average errors in the relevant KPIs reported by the device under the LTE condition being tested. For cellular devices, we considered the LTE test condition to have "no impact" on the device if the device passed the 3GPP tests (as defined by the 3GPP specification) under both the baseline condition and the LTE test condition.

3. Summary of Results and Conclusions

We conclude that Ligado's proposed LTE deployment is clearly compatible with existing GPS operations as implemented by leading device manufacturers.

- GLN:

  - All 12 GLN devices tested — representing five manufacturers — maintained their baseline GPS position accuracy in the presence of Ligado's proposed operations under Open Sky conditions.

  - One GLN device — out of 12 tested — showed an impact from LTE operations in one of the four proposed LTE bands (the 1627.5 - 1637.5 MHz band). This impact to the GPS device from proposed operations in that band was observed only when the device was in motion, was receiving impaired GPS signals, and when LTE signal at the GPS device was above -30 dBm, an event that will occur with extremely low probability.

- Cellular:

  - All three cellular devices tested (one tablet and two cell phones) maintained their baseline GPS position accuracy in the presence of Ligado's proposed operations.[12] In addition, comparing the performance of the Galaxy S6 with its predecessor, the S5, shows that cellular GPS devices' performance, which already is highly robust, continues to improve. This is consistent with the fact that cellular devices include multiple transmitters and receivers (cellular in multiple bands, Bluetooth, Wi-Fi, etc.) collocated with the GPS receiver, which necessitates a design tolerant of other signals.

- Non-Certified Aviation: This device maintained its baseline GPS position accuracy in the presence of Ligado's proposed operations.

- High Precision:

  - We completed testing on a total of 11 devices, produced by four manufacturers.[13]

  - Two manufacturers — Trimble and NavCom — offer devices that, in stock condition, maintain their baseline GPS position accuracy in the presence of Ligado's proposed operations. Four of the 11 tested devices are in this category.

  - One of these manufacturers — Trimble — also offers devices that, although they showed an impact from Ligado's proposed operations in stock condition, showed no such impact when the device's stock antenna was replaced with a filtered antenna. Three devices are in this category.

  - One manufacturer's device — the NovAtel device — is intended for maritime or agricultural use, and accordingly would be unlikely to experience the received LTE power levels in a real world environment at which the device showed a performance impact in the test environment.

---

[12] We were unable to obtain useable data from the Apple iPad.

[13] We were unable to obtain useable data from the Deere Starfire 3000. Nonetheless, we understand that, in any case, Deere does not object to Ligado's proposed operations, subject to the license modifications Ligado has requested from the FCC.

- The remaining manufacturer — Topcon — offers devices that show an impact from Ligado's proposed operations only in the 1526-1536 MHz band. Three devices are in this category. Note, however, that our analysis did not consider the effect of any additional (deferential) power limits Ligado may be subject to in connection with its request that the FCC condition Ligado's licenses on power limitation requirements for the 1526-1536 MHz band necessary to achieve compatibility with current and future MOPS that are incorporated into an active Technical Standard Order from the FAA at a later time.

Finally, our testing found no meaningful correlation between 1 dB change in C/N_0 and GPS device's KPI performance. Indeed, average C/N_0 values reported by the receiver (averaged over all GPS satellites) showed random variations in excess of 1 dB in the absence of any adjacent band signals, and such variations did not accurately predict a device's position accuracy.

Attachments

GPS and Adjacent Band Co-Existence Study:

Summary of Method and Results

May 9, 2016

Roberson and Associates, LLC
Technology and Management Consultants